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WHITE LIGHT FROM THE MERCURY ARC AND ITS COMPLEMENTARY.

By Herbert E. Ives.

Attempts have been made to modify the color and unpleasant illuminating characteristics of the mercury vacuum arc by the addition of yellower light sources. The first light used for this purpose was the carbon glow lamp. More recently, in an article which appeared since the present investigation was started, the use of a tungsten lamp is described.[1]

In the present paper is recorded an experimental investigation of the proper light source to be combined with the mercury arc in order to imitate average daylight, following which is a determination of the relative intensities of mercury arc light and the added light to secure the best effect.

In a recently published article,[2] the writer has considered the question of producing white light by screening some of the more common illuminants. The problem of combining lights to produce white can be treated by use of the same data and in a similar manner. As, however, the only case at present occurring of lights suitable for this purpose is that of the mercury arc and its complementary, this was reserved for separate detailed discussion and experimental test.

The complementary of the mercury arc may be determined by direct application of color theory to experimentally obtained color values, as, for instance, spectrophotometer data. First, find the spectrum hue of the mercury arc (as is done in the paper above referred to); secondly, find the complementary hue, or hue to be added to produce white; then select a light having that dominant hue. From the color-sensation values of the two sources, and the intensity values of the sensations, the candlepower relations of the two to give white are calculable. On carrying through this work, the rather unexpected result was obtained that the best combination was of the mercury arc with a Welsbach; unexpected, because the usual criticism of both illuminants is on the ground of their green color, or illuminating effect.

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[1] A. J. Marshall. Transactions of the Illuminating Engineering Society, April, 1909.

[2] Illuminating Engineer, October, 1909.

In the present investigation, a method similar in principle to the above-outlined theoretical discussion was used, differing from it, however, in that it affords an opportunity to make an exact experimental comparison of the combination decided upon with the standard white it is desired to imitate. The Ives colorimeter was employed, together with Maxwell's color triangle.

The Ives colorimeter, designed by Frederic E. Ives, is essentially a color-mixing machine, mixing red, green, and blue light to produce a visual match with the color measured. White being taken as equal parts red, green, and blue, other colors are numerically described by the proportionate parts of the three primaries which mix to match them. Various light sources have been measured by the writer, among them daylight of various qualities, and the artificial illuminants compared with the average of the daylight measurements as a standard.[3] By means of several of the illuminants which were measured in that investigation it is possible, at any time, to determine the setting of the instrument to give "average daylight," and then compare any artificial white light with it. This possibility made available a verification of the correctness of the work here outlined; had there been no more scientific method of attaining the end, a purely experimental mixing of various sources could have been tried and the best mixture selected. As stated above, use was made of Maxwell's color triangle to guide to the proper selection of complementary to the mercury arc. As the color triangle and its properties are not widely known, a paragraph may be devoted to it.

If we represent the red, green, and blue, which mixed make white, by the vertices of an equilateral triangle, then all points within the triangle can represent mixtures of red, green, and blue in various proportions. We avail ourselves of the property of an

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[3] Transactions of the Illuminating Engineering Society, November, 1908.

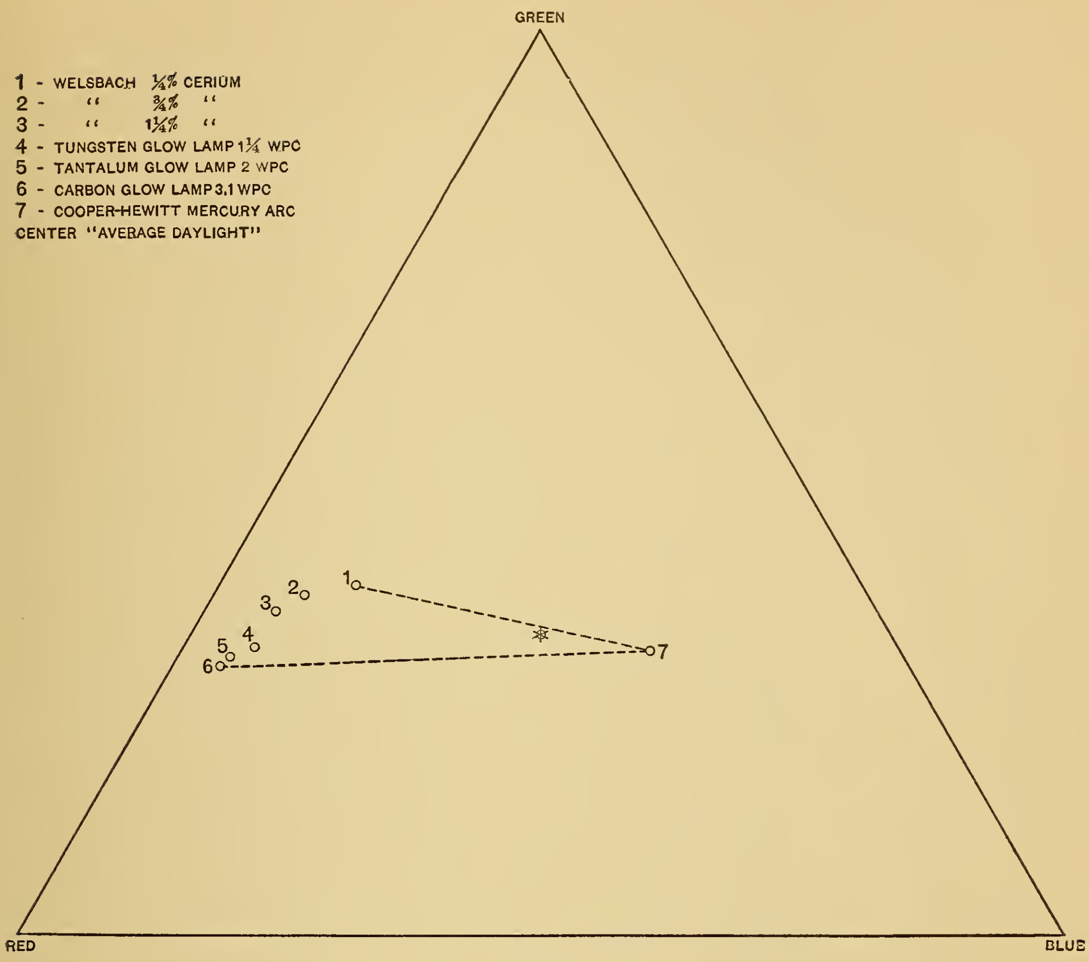

Fig. 1.

TABLE I.

Colorimeter Measurements of Illuminants.

		Red	Green	Blue	Cp to 1 cp of Hg light	Efficiency of combination
1	Welsbach ¼ per cent cerium..........	48.7	38.3	13.0	....	....
2	Welsbach ¾ per cent cerium..........	54.0	37.4	8.6	.57	....
3	Welsbach 1¼ per cent cerium........	57.5	35.5	7.0	....	....
4	Tungsten glow lamp 1¼ wpc..........	61.4	31.7	6.9	.54	0.8 wpc
5	Tantalum glow lamp 2.00 wpc (similar in color to Gem 2.5 wpc)...........	64.6	30.4	5.0	....	....
6	Carbon glow lamp 3.1 wpc............	65.7	29.8	4.5	.50	1.4 wpc
7	Cooper-Hewitt mercury arc...........	24.1	31.4	44.5	....	....

equilateral triangle, that the sum of the perpendicular distances of any point from the three sides is constant, and is equal to the altitude. We first express the red, green, and blue representing a color, so that their sum equals the altitude of the triangle, in convenient units. If, then, the vertical distance of a point from the side opposite, say, the red vertex, represents the amount of red, and similarly for green and blue, every color is represented by a point in the triangle. Colors matched by mixing two primaries lie on the sides; white (equal parts of the three primaries) lies at the center. The most important property for our present investigation is this: Mixtures of two colors are represented by points on the line joining the two; therefore two colors which lie on opposite ends of a line through the center are complementary, i. e., will mix to produce white.

In Fig. 1 is given a color triangle in which the red, green, and blue are the primaries of the Ives colorimeter when used as described in the paper referred to. The various light sources measured are plotted from the figures in Table 1, where the values are expressed so that their sum = 100 = altitude of triangle. These figures are from new measurements made for this paper.

An interesting fact brought out by this diagram is that all of the ordinary light sources, from the 3.1 watt carbon lamp to the "greenest" Welsbach (¼ per cent cerium), lie so nearly opposite the mercury arc that a respectable white may be produced by mixing any one of them with it in the proper proportion. The light lying most nearly opposite the mercury arc is the Welsbach mantle, as supplied for residential lighting, viz, ¾ per cent cerium; of the glow lamps the tungsten is nearest the ideal complementary.

The results obtained from the diagram were checked experimentally for the three cases considered of most interest—the Welsbach, the tungsten, and the 3.1-watt carbon lamp. The first two not only come the nearest to the proper hue, but because of their efficiency and cheapness are distinctly practical possibilities. A Cooper-Hewitt lamp was provided with an adjustable cardboard shutter so that more or less mercury light could illuminate the plane of measurement. The Welsbach and the glow lamps were placed, in succession, directly before the tube and immediately below the opening in the shutter. In this way it was possible to vary the mixing proportions at will. The colorimeter was adjusted by measurements on glow lamps of known color values, so that one-half its field showed "average daylight," then the shutter over the mercury tube was raised or lowered (intensity match being preserved by opening or closing the comparison slit of the colorimeter) until the nearest match was found. With the Welsbach and tungsten it was found possible to obtain an extremely close match, the Welsbach match tending slightly toward green and the tungsten toward pink, but by such small amounts that the slight differences of adjustment in several such experiments made at one time one and at another time the other mixture appear a perfect match with the standard. The carbon glow lamp formed, with the mercury arc light, a decidedly pinkish mixture. The indications of the color triangle were therefore entirely borne out.

For practical purposes, the important information to be derived from such an experiment is the candlepower relations between the two lights to be mixed. To obtain these it was necessary to measure the relative intensity of each component illumination as actually obtained on the surface observed during the measurement. The most convenient method was to extinguish each of the two lights of a mixture in turn and measure the illumination from the remaining one. As unit of intensity, the green light of the colorimeter was taken, that is, the red and blue slits were closed, the green slit opened until an intensity match was found, and the opening of the slit read. This, of course, involved comparison of two widely differently colored fields. By taking numerous readings and checking the results by the fact that the sum of the two intensities agreed closely with the intensity of the mixture measured in the same way, sufficient accuracy was obtained, it is believed, for the present purpose.

The values found were as follows: To one candlepower of mercury arc light should be added, to make white, .57 cp of Welsbach light; .54 cp of tungsten; .50 cp of 3.1 carbon light. Practically, therefore, we may say that we must add to the mercury arc a little over half its candlepower of Welsbach, tungsten, or carbon glow lamp light, to secure white.

It is interesting to compare these figures with those given by Mr. A. J. Marshall in the installation above referred to. There the proportions were: Cooper-Hewitt, 200 cp; tungsten, 80 cp; or a smaller proportion of tungsten than here found best.

Several points in connection with the character of this composite white light should be emphasized. It must not be forgotten that daylight is extremely variable in color, and that the combination of lights here investigated can only claim to be a more definite guide than has hitherto been given to the proportions for a match of the integral color to an average daylight. Further, it is, of course, only the integral color that appears white to the eye; analysis reveals the mercury line spectrum superposed on a continuous background strongest in the red. Because of the partly noncontinuous character of the spectrum of such a compound light, we must expect some deficiencies when it is used as an illuminant of colored objects. The chief defect of the mercury arc alone—its entire deficiency in red—should, however, be largely overcome. Because of the peculiarity of the eye that it quickly adapts its scale of color values to the color of the illuminant, it is much more important, in the writer's opinion, that the illuminant should preserve certain color values to which the eye is particularly sensitive than that its integral color should be a perfect subjective white. In other words, the eye quickly adjusts itself to the belief that a light is "white" even if the light is measurably yellower or pinker than a standard such as average daylight or sunlight, but rebels at a distortion of its new scale of color values. Therefore our preference should be given to that illuminant of this character which favors preservation of color values to which the eye is particularly sensitive, such as the color of flesh, lips, and other commonly observed objects.

The combinations under discussion were investigated for their color rendering values by observing their effect on various colored silks, plaids, colored prints, flesh, etc. The color values were, on the whole, found to be very well preserved; immeasurably more so than with the mercury arc alone, and much better for blues than with the yellower sources alone. A slight accentuation of purples and a graying of very deep reds was observable with both combinations (Welsbach and tungsten), but ordinary reds, browns, yellows, greens, and blues appeared normal. The tungsten lamp, with its larger proportion of deep red, is appreciably better in this combination than is the Welsbach, judged by this criterion. For the best results in color rendering, apart from the integral color of the mixture, a larger proportion of the tungsten light rather than a smaller might be recommended, because, as remarked above, the resultant pinkish character of the white would be less noticed by the eye than the disturbance of the scale of color values which occurs with a deficiency of continuous spectrum background. The behavior of the carbon lamp is similar to the tungsten, although the integral color is too pink to be called a good white.

The results of the above investigation are as follows: The Welsbach and the tungsten glow lamp are shown to be most nearly complementary in color, of the ordinary illuminants, to the mercury arc; the proportions in which their light should be added to the light of the mercury arc to produce white are determined; study of the color rendering values of the resultant mixtures indicates that the tungsten combination is the more desirable, and that the proportions given may be considered a lower limit to the amount of tungsten light to be added for satisfactory illumination of colored objects. The carbon glow lamp is also investigated and compared with the others in this combination.

An approximate idea of the efficiency of the combination of mercury arc and glow lamps is easily obtained. For the tungsten lamp combination we find, assuming 1.25 wpc for tungsten and .55 wpc for the Cooper-Hewitt, that 1.54 cp is obtained at an expenditure of 1.22 watts, or an efficiency of .80 wpc. For the 3.1 carbon lamp we obtain, similarly, 1.4 wpc. Therefore the tungsten-mercury combination is not only nearer white, but much more efficient than the carbon lamp combination used at first. The Welsbach-mercury combination can not be expressed in this way, but consideration of expense makes this combination compare closely with the mercury-tungsten one.

WASHINGTON, August 1, 1909.